

Applied Aeroscience and CFD Branch Rarefied Gas Dynamics Discipline Overview

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UT Seminar – 4/9/2015

Presentation Overview



- NASA JSC
 - Applied Aeroscience and CFD Branch
 - Rarefied Gas Dynamics (RGD) Discipline
- RGD Tasks:
 - Tools
 - Direct Simulation Monte Carlo (DSMC) Analysis Code (DAC)
 - Program support
 - ISS
 - Orion
 - Commercial Crew

Lyndon B. Johnson Space Center

Principal Mission: Human Spaceflight



The Future of Human Space Exploration

NASA's Building Blocks to Mars

U.S. companies
provide
affordable
access to low
Earth orbit

Learning the
fundamentals
aboard the
International
Space Station

Expanding capabilities
by visiting an asteroid
in a Lunar distant
retrograde orbit

Traveling beyond low Earth
orbit with the Space Launch
System rocket and Orion crew
capsule

Exploring Mars
and other deep
space
destinations

*Missions: 6 to 12 months
Return: hours*

*Missions: 1 month up to 12 months
Return: days*

*Missions: 2 to 3 years
Return: months*

April 9, 2015

Earth Reliant

4

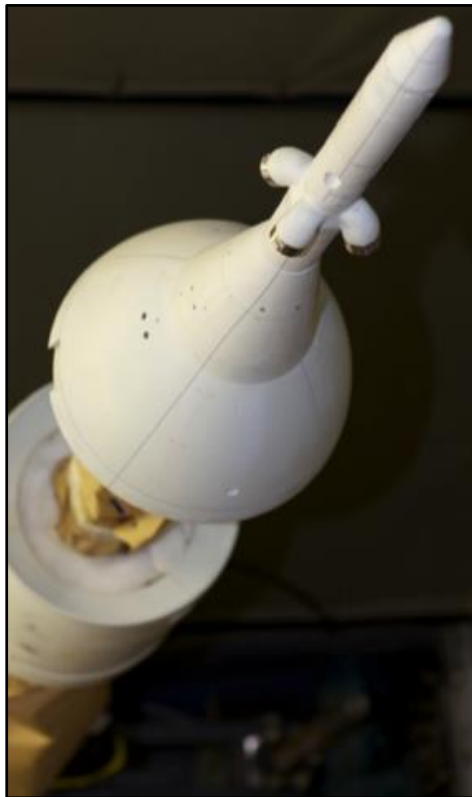
Proving Ground

Earth Independent

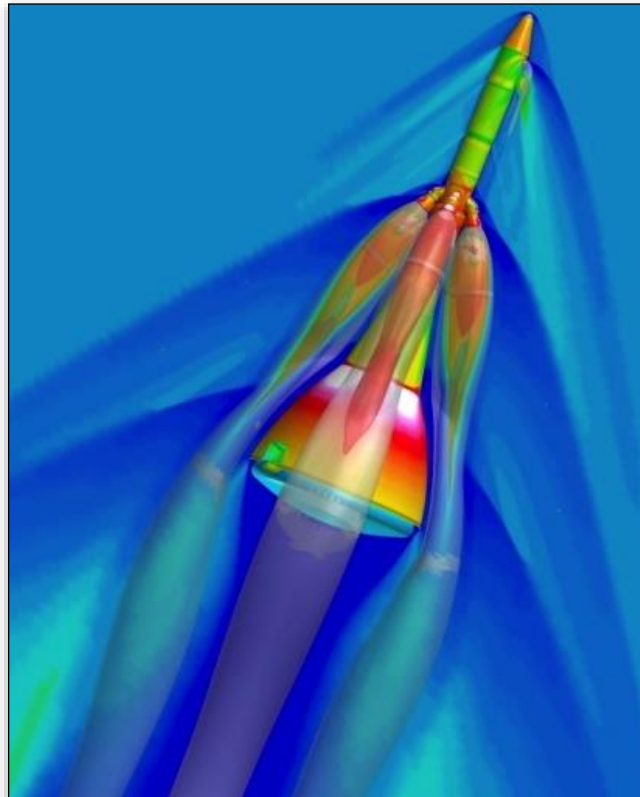
Applied Aeroscience and CFD Branch



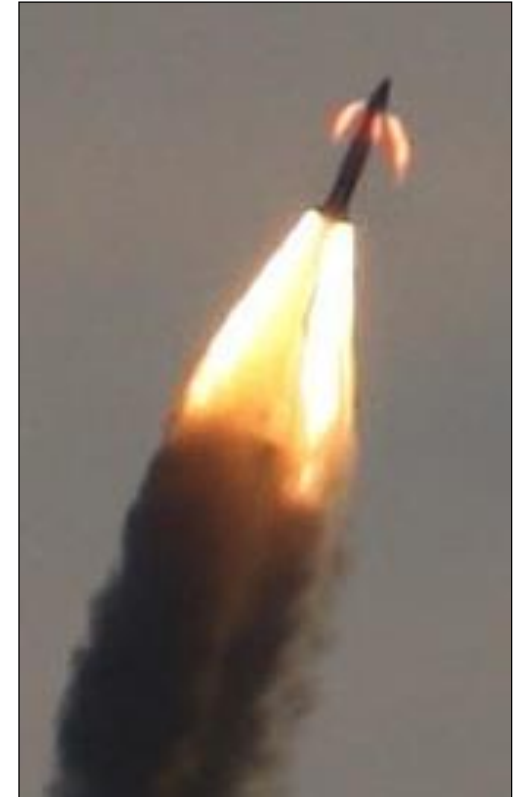
- (1) Aerodynamic Characterization
- (2) Aerothermodynamic Heating
- (3) Rarefied Gas Dynamics (RGD) Discipline
- (4) Decelerator (Parachute)



Ground Testing

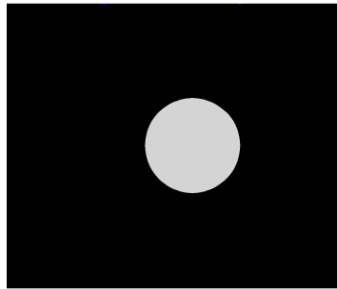


Modeling and Simulation

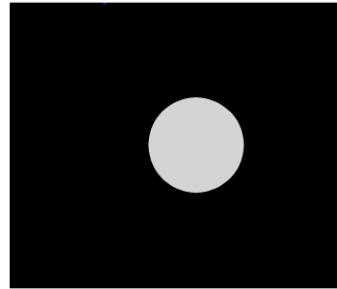


Flight Testing

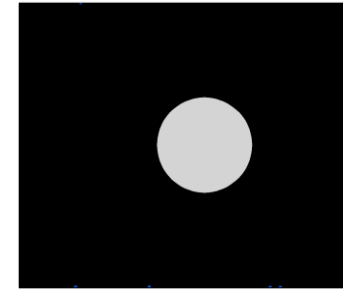
Rarefied Gas Dynamics



Continuum - CFD



Transition - DSMC



Free Molecular

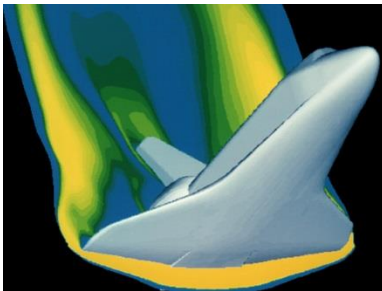
~0.01

~100

Kn

CFD

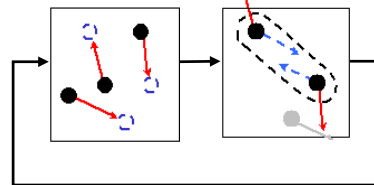
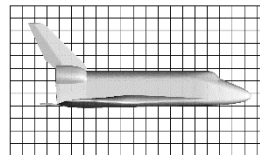
(Comp. Fluid Dyn.)



- Partial Diff. Equation Based
- Numerical Methods employed to obtain approximate solution
- Continuum Assumption
 - Invalid at large Knudsen #

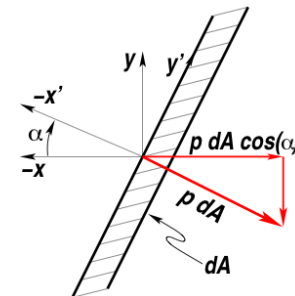
DSMC

(Molecular Based)



Move Collide

Free Molecular Aerodynamics

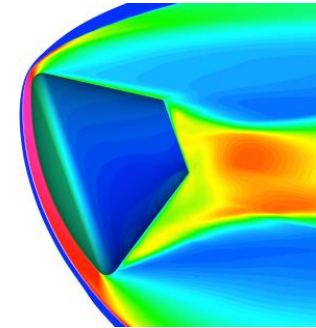


$$C_p = \cos^2 \alpha \left[\frac{1}{S_v} \left(\frac{1}{\sqrt{\rho}} + \frac{1}{2S_v} \sqrt{\frac{T_r}{T_i}} \right) + \frac{1}{2S_v^2} \sqrt{\frac{T_r}{T_i}} e^{-S_v^2} \right] + \frac{1}{2S_v^2} \sqrt{\frac{T_r}{T_i}} e^{-S_v^2} \left[1 + \text{erf}(S_v) \right]$$

Rarefied Gas Dynamics Discipline Overview



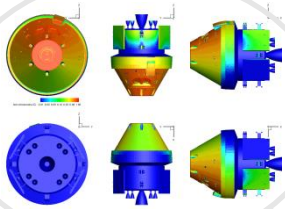
- Objective:
 - Provide state-of-the-art capabilities and tools for analysis of a variety of low density, non-continuum flows (from transitional to free molecular)
- Methods:
 - Mainly computational modeling
- Tools:
 - **DAC (DSMC code)**
 - RPM3D (Engineering tool for plume impingement analyses)
 - FREEMO (Free molecular code)
 - Other computational tools (RAMP, BLIMP, DPLR, ...)
- Customers:
 - **International Space Station**
 - Orion
 - Commercial Crew



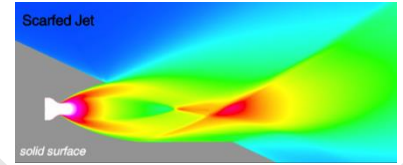
Rarefied Gas Dynamics Discipline Products



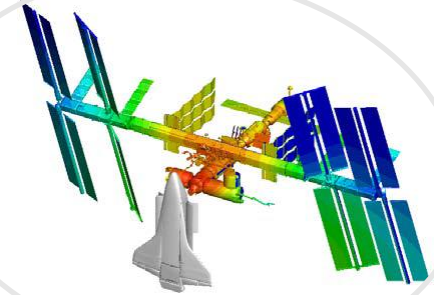
Aeroheating



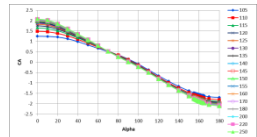
Plume modeling



Plume impingement



Aerodynamics



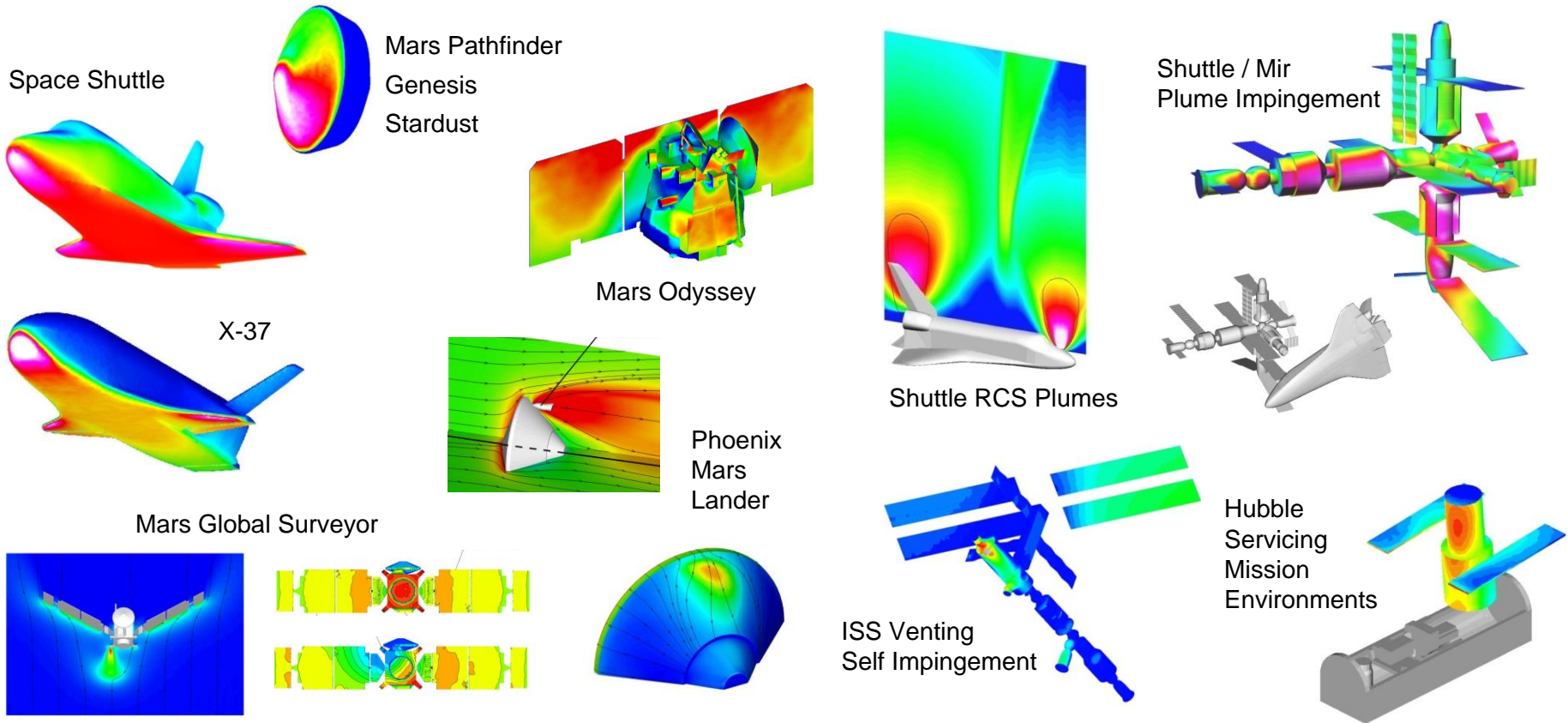
Free Molecular

Transitional

Continuum



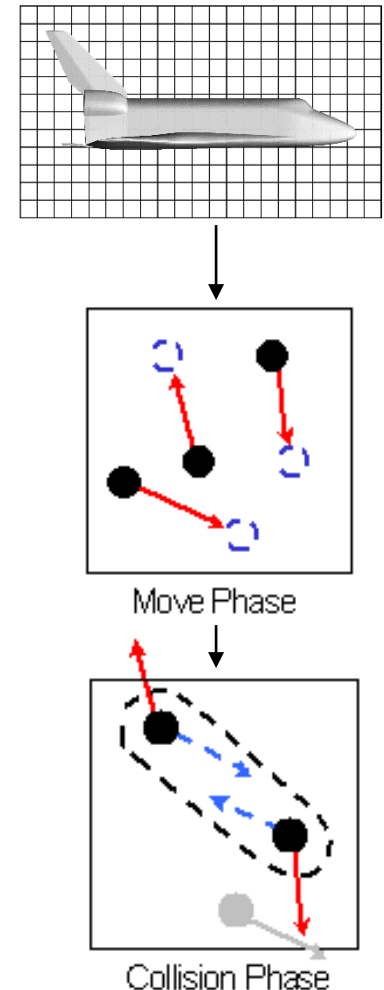
Direct Simulation Monte Carlo (DSMC) Analysis Code (DAC)



Direct Simulation Monte Carlo (DSMC)



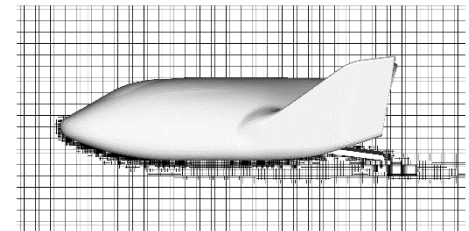
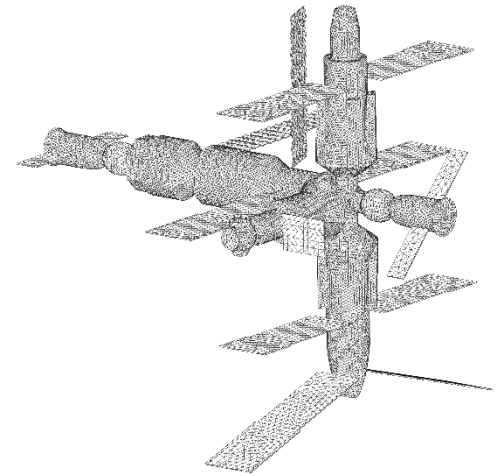
- Simulated molecules tracked through space and time.
 - Each simulated molecule represents many real molecules.
- Network of flow field cells used to group neighboring molecules into collision pairs.
- Move and collision phases decoupled and treated as distinct computational steps.
 - Move step is deterministic.
 - Collision step is a Monte-Carlo simulation of kinetic theory based collision statistics.
- Statistical sampling of the ensemble of molecules provides macroscopic properties.
- Fundamental requirements on simulation parameters must be satisfied to achieve an accurate result.
- Results shown to be equivalent to solutions of the Boltzmann equation.



DSMC Analysis Code (DAC)



- Geometric and boundary condition flexibility and gas chemistry options allow a wide variety of rarefied problems to be analyzed.
 - Including on-orbit plumes
- Provides automatic flow field discretization and solution adaptation such that fundamental simulation constraints are satisfied.
- Enabling feature of DAC is its ability to easily and efficiently utilize a large number of processors on a single problem.
 - Automatically performs domain decomposition
 - Re-partitions domain decomposition during runtime to maintain load balancing
 - A halted run can be restarted on a different number of processors
- The above features provide “ease of use” as well as versatile capabilities.



DAC Software



- A general purpose DSMC implementation
 - Pre-Processor PREDAC / DPREDAC
 - Run Code DAC / DDAC
 - Flow Field Post-Processor SLICE
 - Surface Post-Processor SPROP
 - Utility Code STP
- Written primarily in “Modern” FORTRAN
 - Small amount of C (timing, 3rd party Delaunay routine)
- Uses the Message Passing Interface (MPI) message passing scheme to effect communication between the processors
- Initially developed for execution on a heterogeneous “cluster” of workstations
- Grew out of a homework assignment...
- ITAR but freely available

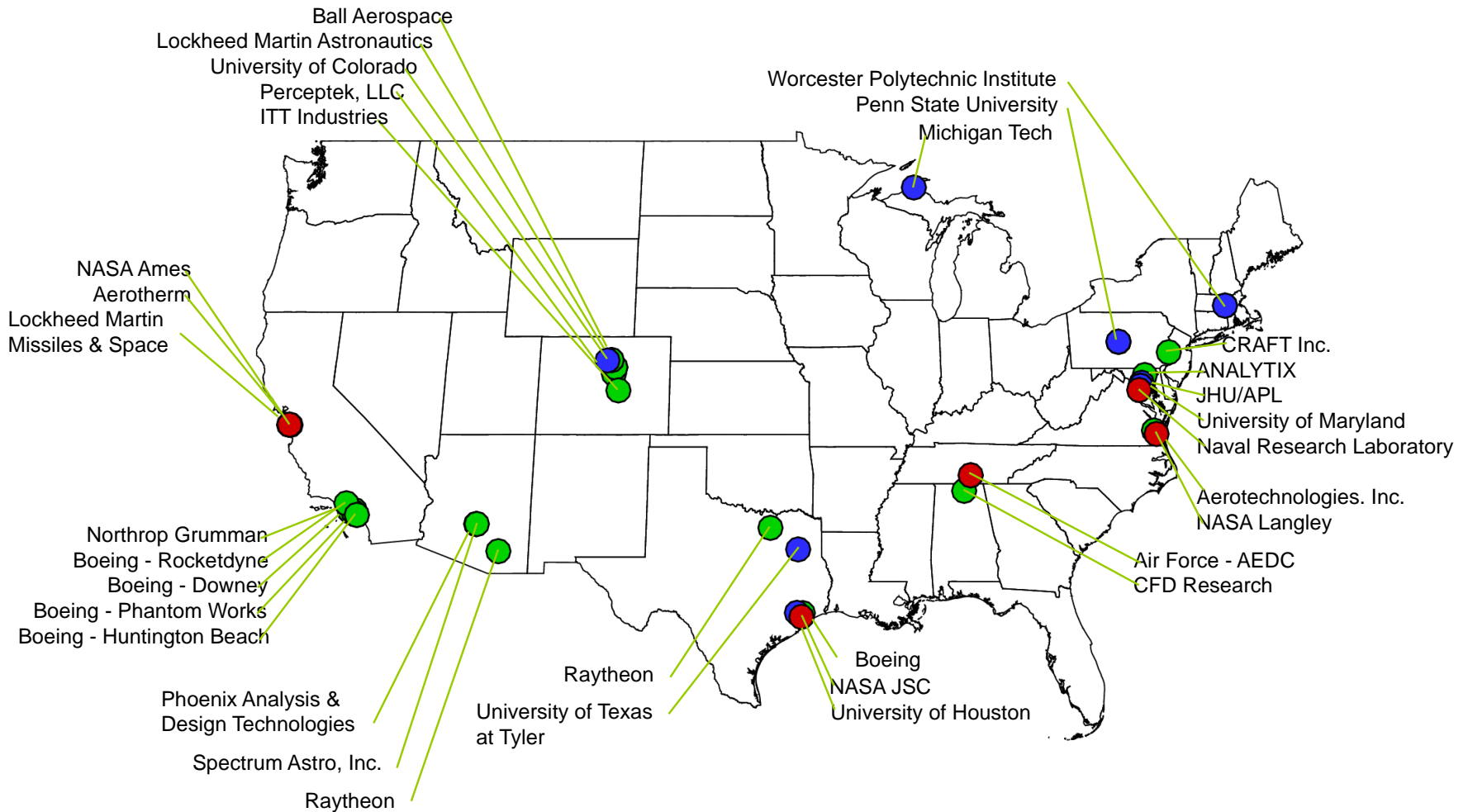
DAC's User Base



● NASA or DoD

● Industry

● University



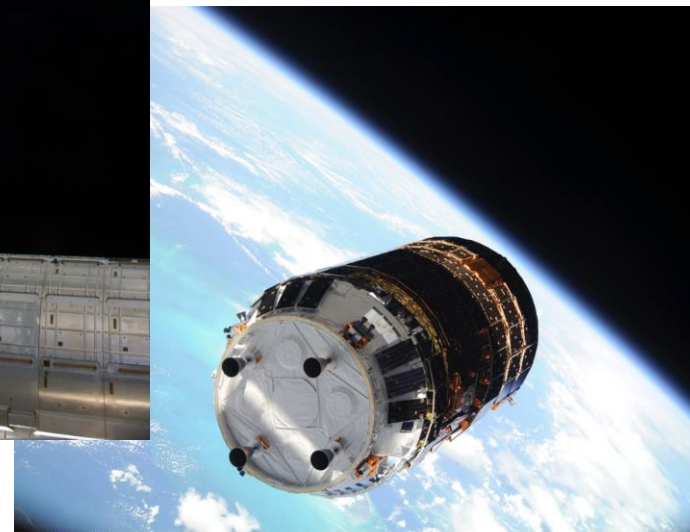
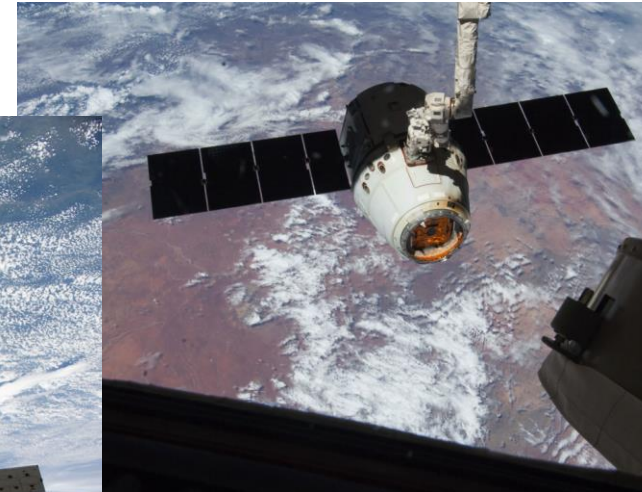
International Space Station Support



International Space Station Proximity Operations



- Three resupply vehicles HTV, Cygnus and Dragon berth to ISS US segment
- Need to verify their Monte-Carlo trajectories to make sure that they follow ISS requirements during their Proximity Operations
 - Loads
 - **Heating**
 - Contamination
- Use an engineering tool (RPM3D) to screen the trajectories
- Use high fidelity tool (DAC) for specific analyses



ISS020E041290

Proximity Operations Screening



- Quick engineering tools are desired
 - Need to examine hundreds of thousands of plume impingements
 - Thousands of plume events per docking
 - Must assess hundreds of dockings
- Can decompose into freely expanding flow and impingement analyses
- Vacuum plumes flow fields can be approximated by a source flow
- Impingement can be handled with bridging between Newtonian and free molecular expressions for pressure, shear, and heating.

Plume Modeling

The diagram illustrates the geometry of plume modeling. On the left, a nozzle is shown with a dashed horizontal axis. A point is defined by its radial distance r from the nozzle and its angular position θ relative to the axis. To the right, a rectangular surface is shown at an angle α relative to the horizontal axis. Below the diagram, the following equations are provided:

$$\rho = \rho(r, \theta) = f(r)g(\theta); \quad u = u_{\text{lim}} = \sqrt{2\gamma T / (\gamma - 1)}$$
$$P = c_p q = (c_{p0} \sin^2 \alpha) \left(\frac{1}{2} \rho u^2 \right)$$

Proximity Operations Complex Problems

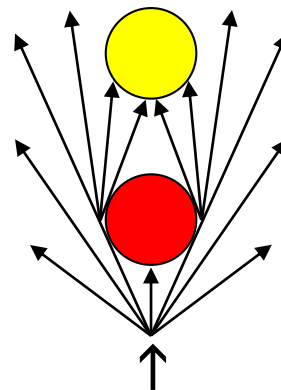
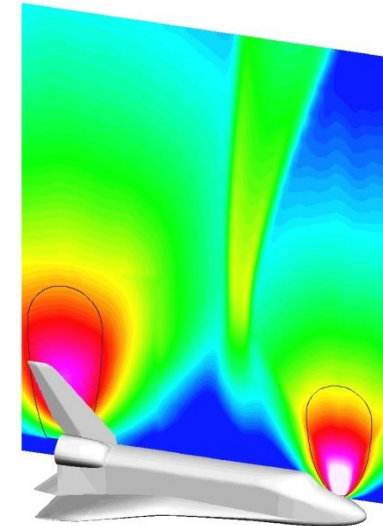
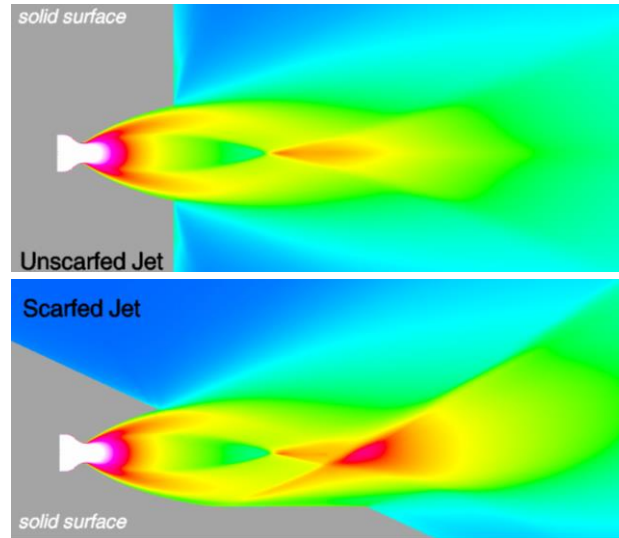


- Complex Plumes

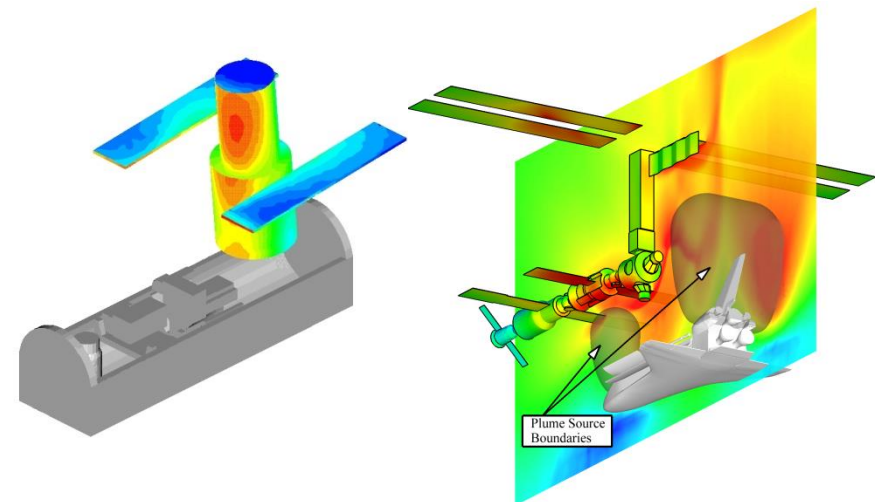
- Scarfed Jets
- Multiple Jets

- Complex Interactions

- Wakes
 - Shadowing
 - Assumption
 - Infinite Mach
 - Free Molecular
 - Flow actually turns
- Complex geometry
 - Target affects plume flow field
 - Multiple Surface Interactions



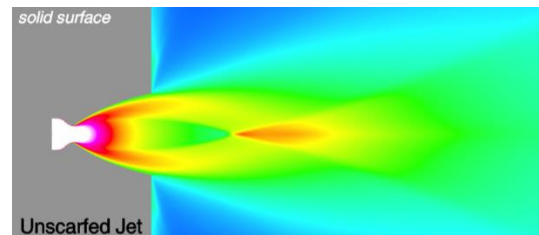
Flow Turning



Complex Plume Impingement Effect Analyses

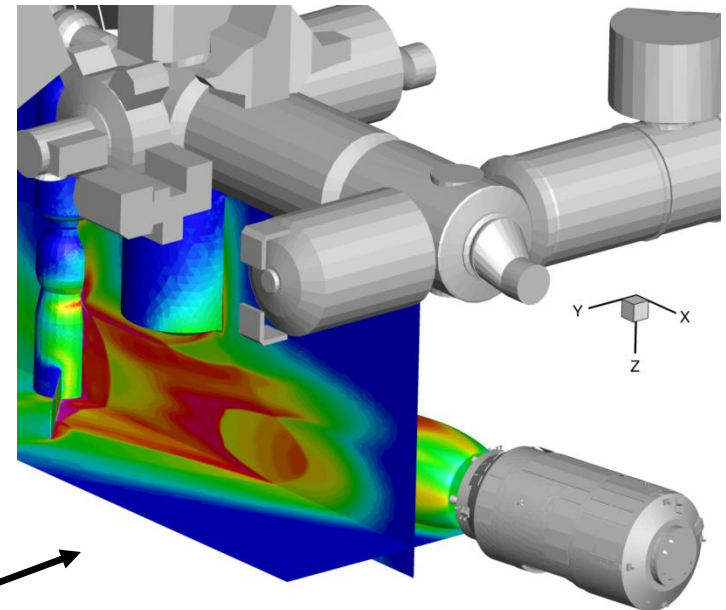
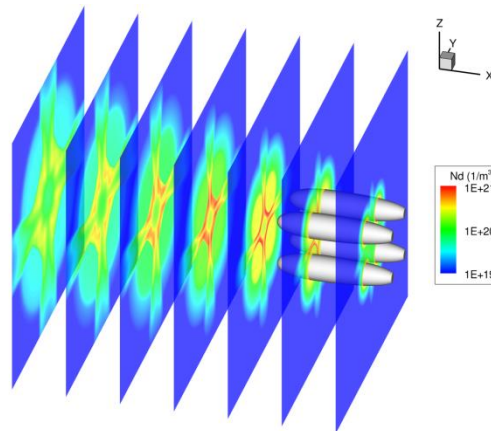


- Flow expands from continuum in the nozzle to free molecular in the far field
- Complex flow fields must be properly modelled at each stage



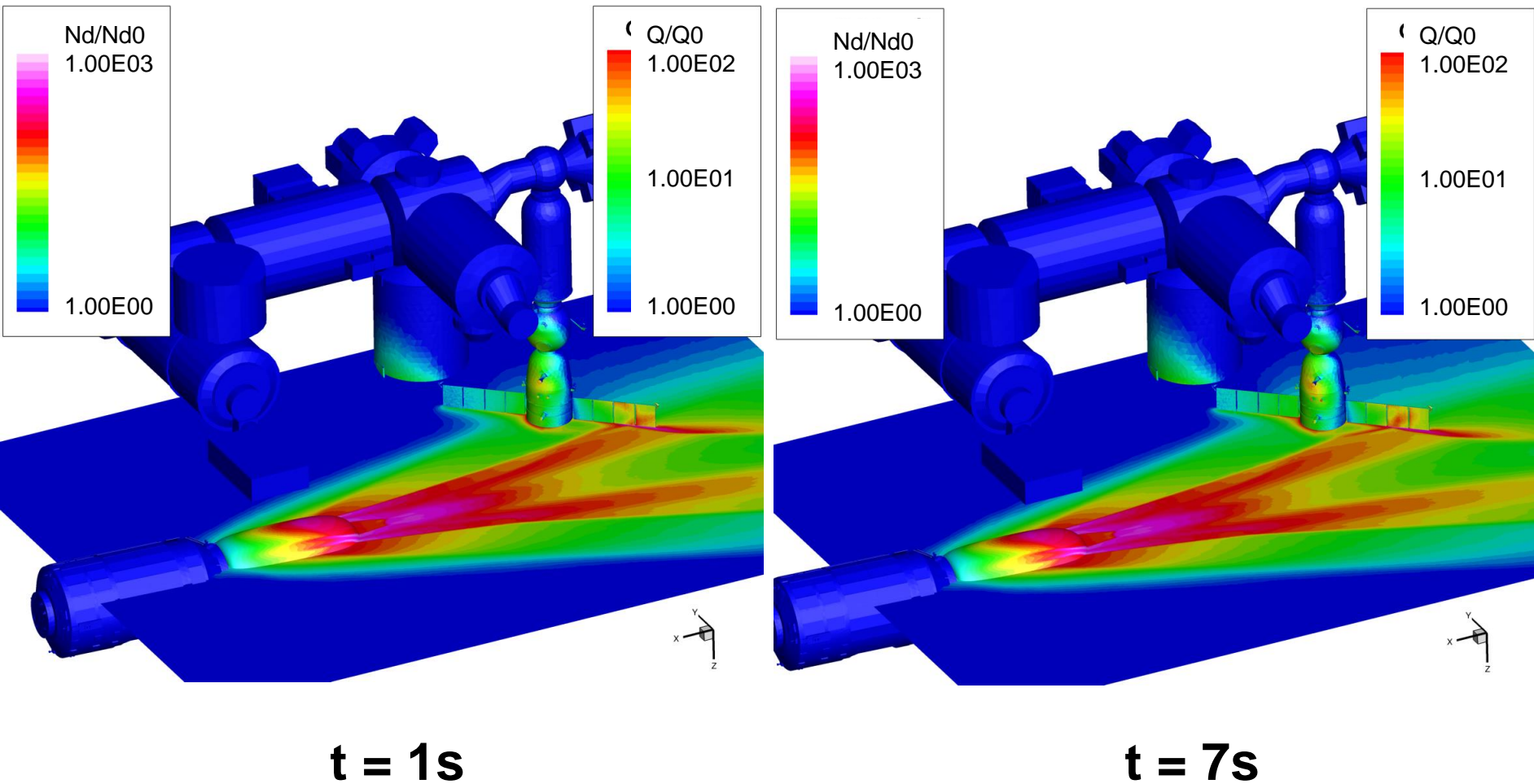
Step 1:
Near field modeling
(Continuum -> CFD)

Step 2:
Far field modeling
(Transitional -> DSMC)



Step 3:
Surface interaction modeling
(Transitional -> DSMC or
Free molecular -> Engineering tool)

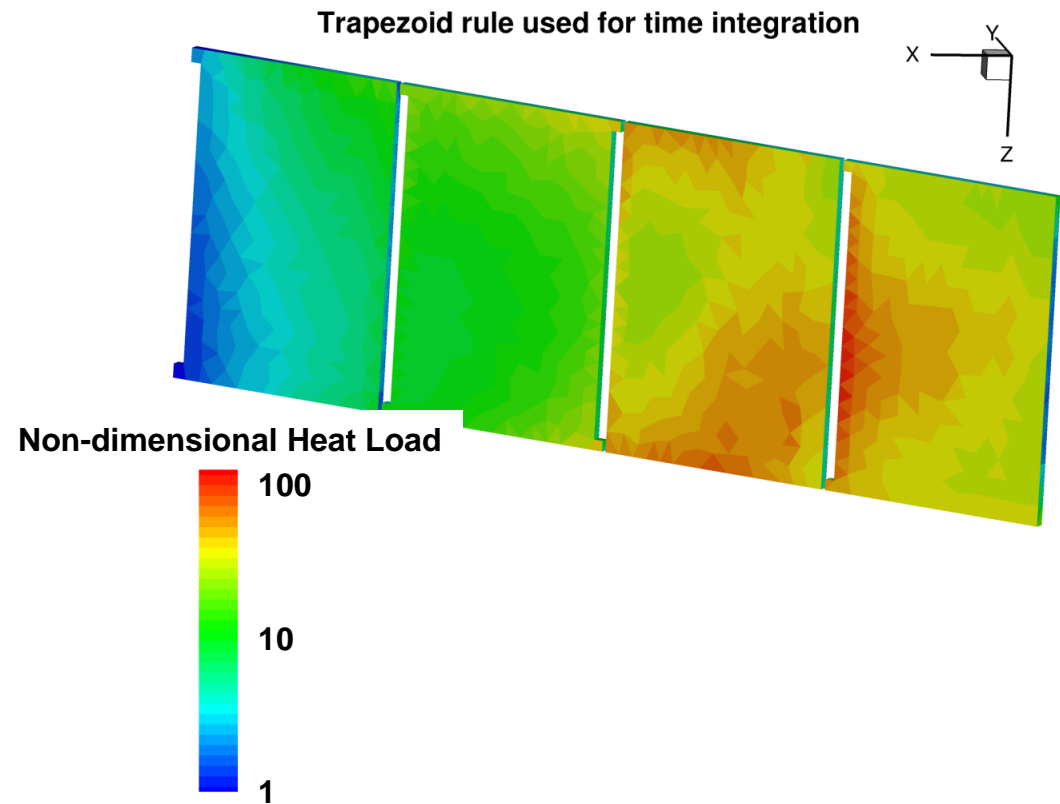
HTV Main Engine Abort Flow Field



HTV Main Engine Abort Heat Load on the Soyuz Array



- Engineering method maximum heat load value = q_0
- DAC maximum heat load value $\sim 65\% q_0$
- Refined analysis required to obtain more accurate results and eliminate unnecessary conservatism

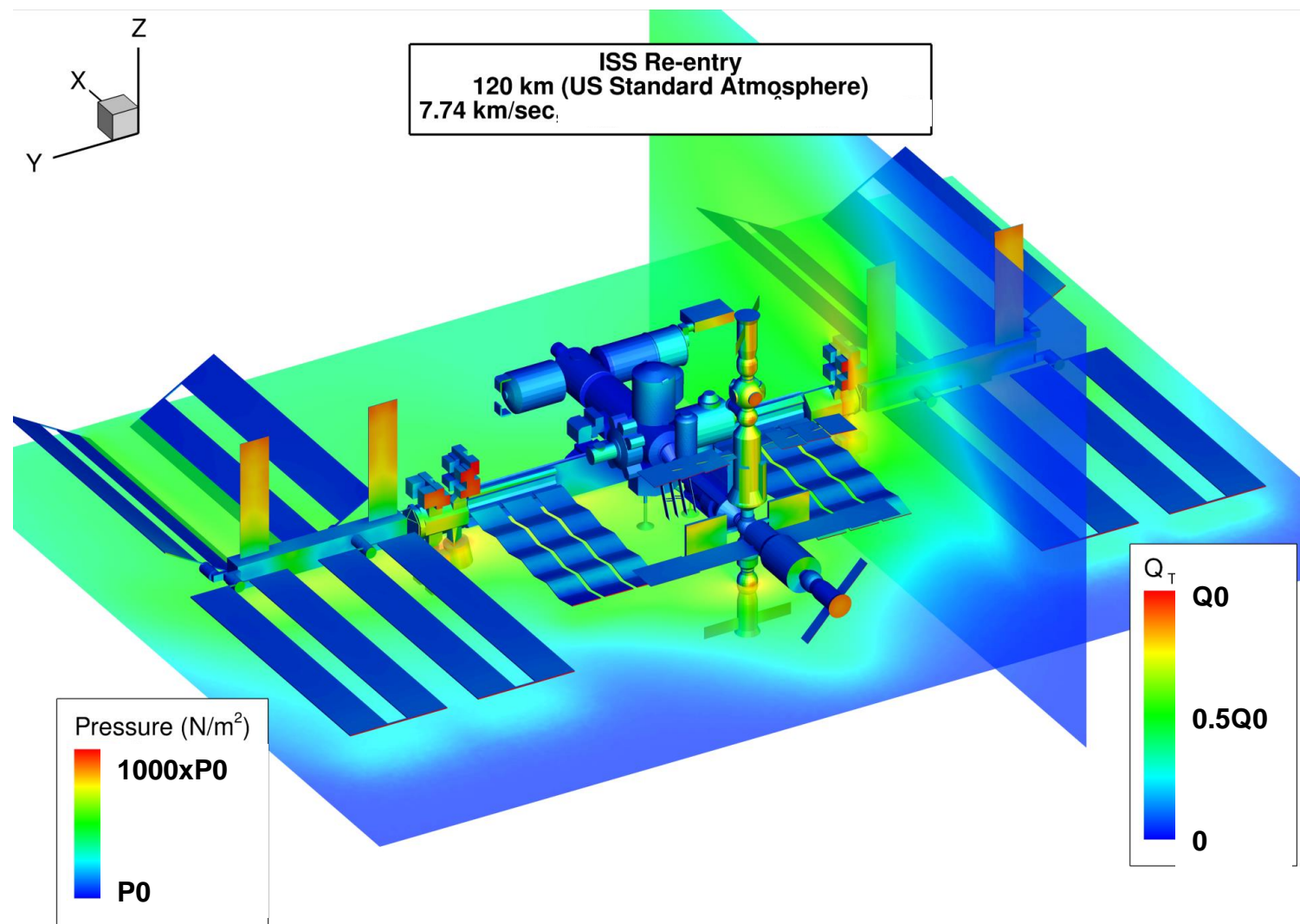


ISS End of Life



- When decommissioned, ISS will de-orbit and will have a targeted fall into the South Pacific Ocean Unpopulated Area
- Challenges:
 - Heaviest vehicle to have a planned de-orbit
 - Complex geometry which limit the Delta-V that can be imparted
- Detailed understanding of the aerodynamics and aeroheating to ISS during the earliest portions (130-105 km) of re-entry will assist in:
 - Determining controllability and initial break up altitude
 - Developing strategies for ISS configuration and attitude plan
- DSMC analyses will provide detailed information of the surface pressures, surface heating, and integrated forces and moments to the ISS during re-entry
 - Detailed physical features such as shock-shock interactions are captured

Surface Heating and Flow Field Pressure



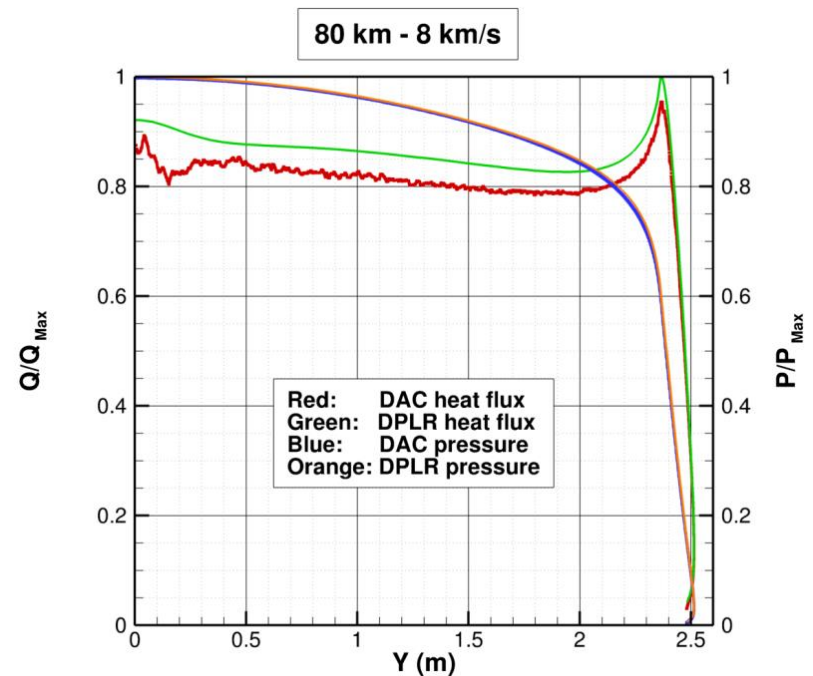
RGD Discipline Challenge: Bridging the gap between CFD and DSMC



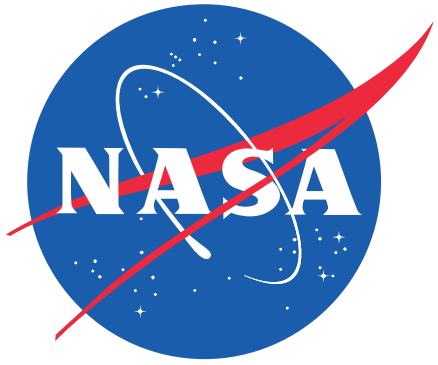
- The DSMC method can be used to model continuum flows but is generally too expensive to use for real-life problems
- For re-entry databases, a bridging function is used between the highest CFD solution and the lowest DSMC solution → not as accurate a model in that region as everywhere else

Challenges:

- Match gas parameters and chemistry models between codes
- Improve the DSMC code efficiency
- Incorporate advanced models in the CFD code to better model the rarefaction effects



Surface properties on a capsule heat shield at 80 km and at zero angle of attack and sideslip angle with out-of-the-box codes



BONUS SLIDES

Orion Exploration Flight Test 1

Orion Exploration Flight Test 1

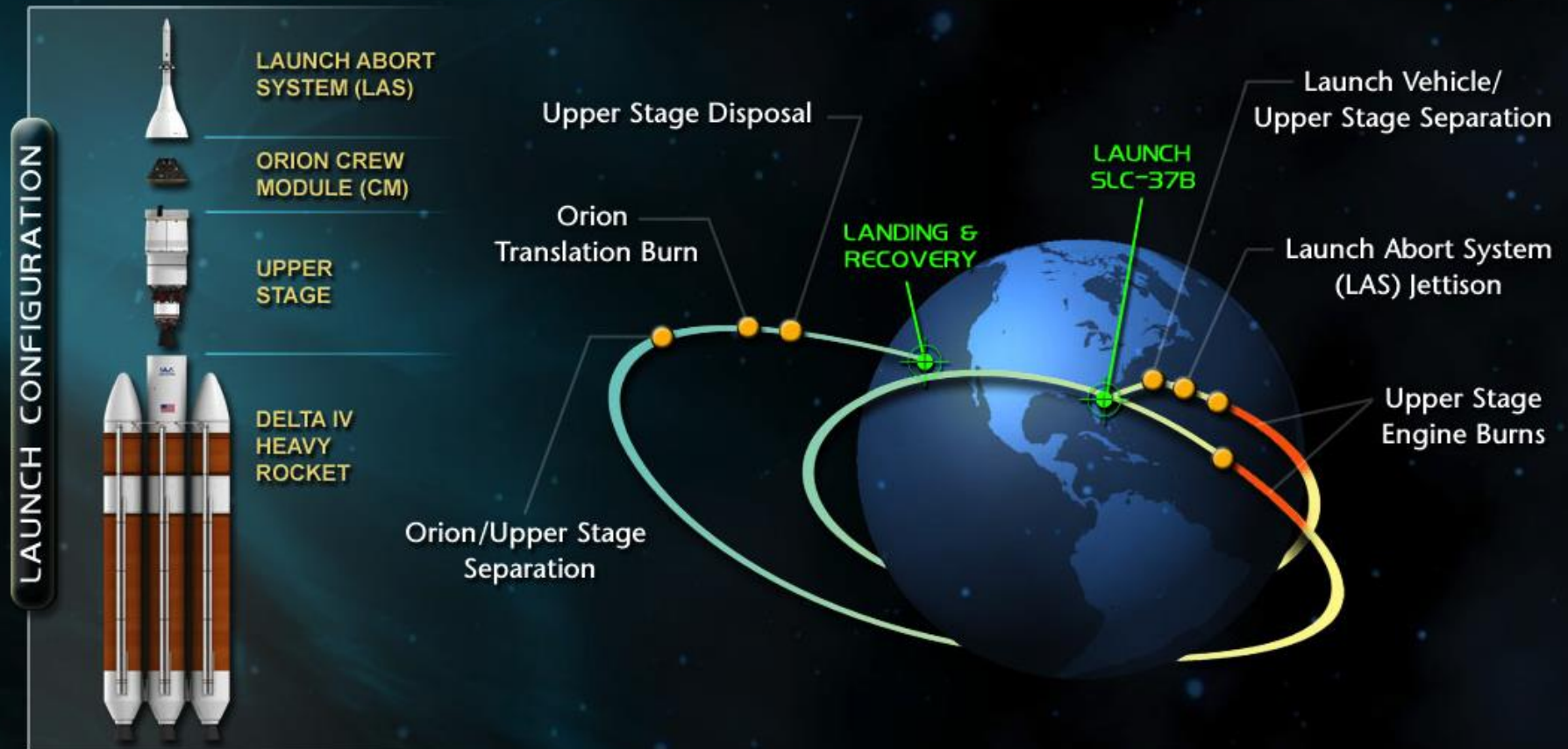
December, 5th 2014



EXPLORATION FLIGHT TEST ONE

OVERVIEW

TWO ORBITS • 20,000 MPH ENTRY • 3,671 MILE APOGEE • 28.6 DEGREE INCLINATION



Orion Exploration Flight Test 1



Launch



Splashdown

